research review

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DOUBLE OPTICAL RESONANCE SPECTROSCOPY

DENTON W. ELLIOTT, Directorate of Chemical Sciences, AFOSR

Dr. Thomas Dunn, a University of Michigan grantee of the Directorate of Chemical Sciences, AFOSR, has been exploiting a technique known as double optical resonance spectroscopy (DOR).

Since nearly all molecules are in their lowest electronic state at room temperature, their color depends upon how "high" the excited state lies. However, some molecules possess excited electronic states which have comparatively very long lifetimes. If one can get a large number of molecules into these long-lived states, then a beam of light passed through may boost them to even higher excited states, producing a different "color."

Such a molecule is the uranyl ion, UO_2^{++}, since it possesses an excited state which has a half life of about half a millisecond. This may not seem long until one compares it with the usual lifetime of approximately one millionth of a millisecond. This metastable state is obtained when light of blue-green color is absorbed. If a large amount of this light is present, as is the case when a powerful flash lamp is set off close to the uranyl compound, then a large number of uranyl ions go to the excited state. The absorption spectrum of the ions in this state is then taken and is found to have a maximum at 5,800 A.

From such experiments it is possible to find out more about the highly excited states of molecules and so to learn more about those states which are likely to be important when the molecules react with other molecules.

From the foregoing it becomes apparent that the principle involved in DOR spectroscopy is to populate any electronically excited state of the molecule by exposing it to an intense flash of ultraviolet light, and then to boost those same molecules into an even higher state of excitation. This is shown diagramatically in Figure 1, where the primary process is indicated by A, and the final process by D. The intermediate process, B, too fast to be observed, corresponds to intersystem crossing.

Excitation to T_1 cannot occur directly because of the forbidden character of the transition between S_1 and T_1. This, of course, is why the molecules have a long life in the state T_1 before they ultimately fall back to the ground state S_1.

This process has been observed so far for the uranyl ion, UO_2^{++}, and Mn^{2+} in a spinel lattice. In the case of the uranyl ion, the effect can be useful in acting as a Q-spoil for a ruby laser. This can best be seen as follows.

Suppose that two ruby rods are arranged in a line as in Figure 2, and that they are separated by a piece of glass containing the uranyl ion. In addition, let us suppose that good optical mirrors, M_1 and M_2, are at each end of this arrangement so that the ruby crystals are in a Fabry Perot cavity. The flash lamp along the side of the ruby rods is discharged and, as it produces an intense flash of light, it does two things. Firstly, it stimulates the Cr^3 ions of the ruby crystal to excited states from which they can "lase," and secondly, as soon as the flash starts, it causes the UO_2^{++} ions to be excited to the state T_1 discussed above. When the uranyl glass is unexcited, it transmits the red ruby laser light easily (since the glass is yellow!); but when large numbers of UO_2^{++} ions start to populate the level corresponding to T_1, these molecules can absorb ruby laser light and go to level T_2, which just happens to

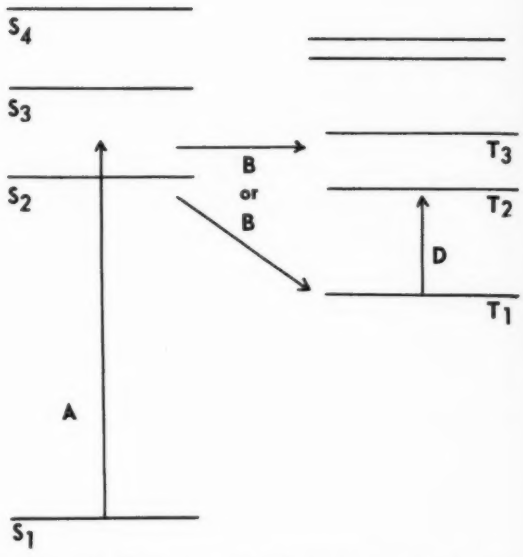

Figure 1. Processes of achieving excited states.

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have the right energy. This transition is a reasonably strong one; so while there are even a few molecules in state T_1, no ruby laser light will be transmitted from the first ruby rod to the second, and there will be no concerted laser action in the optical cavity.

However, as soon as the flash lamp has finished firing, the excited uranyl ion molecules fall back from the T_1 state to the S_1 state in 10^{-6} second. This now allows the cavity to "resonate" optically since there is now a complete optical path from one mirror to the other. The result is that all the energy which is stored up in the excited Cr^3 ions in the ruby rods is now released in one giant pulse.

Because the "Q" of the cavity was "spoilt" by the presence of the UO_2^{++} glass when it absorbed the energy, this process of creating giant flashes is called "Q-spoiling" or just "Q-switching." The same thing can also be accomplished by a rapidly rotating mirror or by various dye solutions. The uranyl glass, however, has the advantage of being very convenient and not appearing to deteriorate, as the organic dye solutions do after a while.

It should be possible, by testing a variety of materials, to find something which will act as a Q switch for almost any frequency of laser light. This could be one of the by-products of this work on DOR.

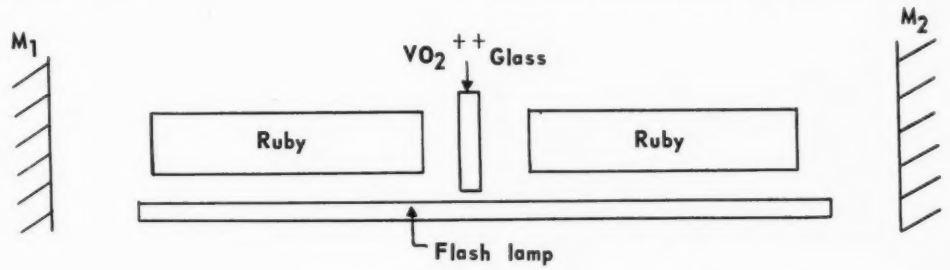

Figure 2. Q-switching technique.

Tunable Band-Pass Filter Using High Dielectric Constant Crystals

MICROWAVE PHYSICS LABORATORY, AFCRL

A new type of tunable band-pass filter with insertion losses of less than 2 db and with an output spectrum of only a few percent of the center frequency has been demonstrated by James C. Sethares and Martin R. Stiglitz of AFCRL. The narrow band-pass filters can be constructed for any desired frequency from 1 to 12 GHz and for either fixed-frequency or tunable operation. Band-pass filters are common components in radio equipments, and in a range of signal-processing instruments.

The basic element of the new filter is a low-loss crystal having a high dielectric constant. Such crystals--rutile and strontium titanate are examples--can be made to resonate at specified microwave frequencies when subjected to an rf field of proper frequency and configuration. When the crystal is placed in a modified waveguide, stripline or other transmission-line structure, it acts as a band-pass filter. That, in essence, is the principle of the new filter.

The band-pass-filter technique was demonstrated at AFCRL by using a waveguide. The crystal (dielectric resonator) is cut in disc form and mounted on a small Teflon or polystyrene post. An iris consisting of a thin sheet of conducting material with a center opening is inserted as a partition inside the waveguide. The resonating disc

is placed in the iris so that it protrudes on either side. When the waveguide is operated above cutoff, the apparatus serves as a band-pass filter.

Different center frequencies are obtained by using crystals with different dielectric constants, and by changing the geometry of the crystal resonator itself. However, any given filter can be tuned over a relatively narrower spectrum either mechanically or magnetically. Mechanical tuning involves mounting two disc resonators inside the waveguide in such a way that they can be brought into contact with each other or moved apart laterally. Separating the resonators results in an increase of the resonator frequency. Tuning ranges of 20 percent of the center frequency have been achieved by this method.

Magnetic tuning is achieved by placing ferrimagnetic materials, such as yttrium iron garnet (YIG), in the vicinity of the dielectric resonator. The ferrimagnet can be disc-shaped and bonded to the disc resonator, or it may be in the form of a sphere or rod, inserted into the dielectric resonator. Tuning is achieved by magnetizing the YIG with an external magnetic field. The basic tuning mechanism involves mode coupling between dimensional resonances of the dielectric resonator and ferrimagnetic resonance of the YIG. It is possible to switch the band-pass center frequency from one value to another in less than a microsecond.

Mr. Martin R. Stiglitz is an electronics engineer with the Microwave Physics Laboratory, AFCRL. He has been engaged in experimental work on phonon generation and the generation of artificial ball lightning. Mr. Stiglitz received the degree of Associate in Mechanical Engineering from the Vienna Polytechnic Institute in 1938, the degree of Associate in Electronic Engineering from Northeastern University in 1957, and a B.S. in Engineering and Management from Northeastern in 1959. He served in the Pacific Theater during World War II, receiving the Air Medal and three battle stars.

Mr. James C. Sethares, a research physicist with the Microwave Physics Laboratory, AFCRL, is investigating magnon-phonon interactions in ferrimagnetic single crystals. His interest in this area began in 1962 when he came to AFCRL. He has a B.S. in Electrical Engineering from the University of Massachusetts (1959), and an S.M. in Electrical Engineering from the Massachusetts Institute of Technology (1962). He has written a number of publications and is a member of the Institute of Electrical and Electronic Engineers.

Tuning ranges of more than 15 percent at X band have been achieved without degradation of the filter response.

When two or more dielectric resonators are placed in the waveguide iris one above the other, and separated by at least one diameter (to minimize mutual field effects), each resonator will pass its inherent frequency band. The combination will act as a dual or multiple frequency filter. Such arrangements using dual resonators were made at C and X band and showed no increase in insertion loss or other adverse effects on filter performance.

Air Force Chief of Staff Presents Awards

In a recent Pentagon ceremony General John P. McConnell (left), Air Force Chief of Staff, presented 1966 USAF Research and Development Awards to five OAR officer-scientists. ARL recipients were (left to right) Lt Col Joseph W. Connolly, 1st Lt Charles S. Springer, Jr., and Dr. Kent J. Eisentraut. Capt William B. Goggins, Jr., of AFCRL and Capt John F. Schaefer of FJSRL (not shown here) also received the awards.

The five OAR men were among seven in the Air Force cited for their research contributions last year.

HORIZONS UNDER STRESS

CAPTAIN JOHN F. KANTAK, Directorate of Engineering Sciences, AFOSR

Research is just beginning to penetrate the mysteries of semiconductor pressure effects. Previously, research had been limited to the exploration of the nature of static mechanical forces on the electrical properties of semiconductor junctions. Now, with the creation of appropriate techniques for producing stress waves, research efforts are being extended into the environment of large dynamic forces.

Large-amplitude static stress research has found relevance in semiconductor accelerometers (Fig. 1). and has also resulted in the construction of a highly sensitive pressure probe (Fig. 2). Unchecked by the constraints of static performance, dynamic research may reveal an unlimited horizon of practical implications. Defining the dynamic response of a semiconductor junction subjected to time-varying pressure should establish multidisciplinary relevance. Bioelectronics may now consider the direct measurement of blood pressure via insertion of the pressure probe into the blood stream. Urologists could examine the forces of the kidney muscles in relation to functional operation. Plasma dynamics in propulsion experiments and local pressures in wind-tunnel experiments might be accurately defined. Flight-control systems using acceleration inputs could be miniaturized and improved. Integrated circuit applications are not beyond the realm of consideration. The range of possible applications appears to be unlimited.

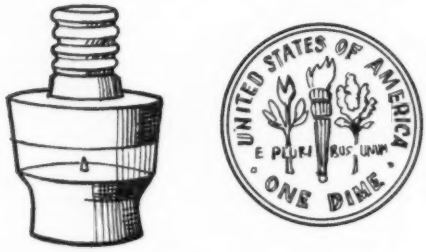

Figure 1. Single-diaphragm accelerometer.

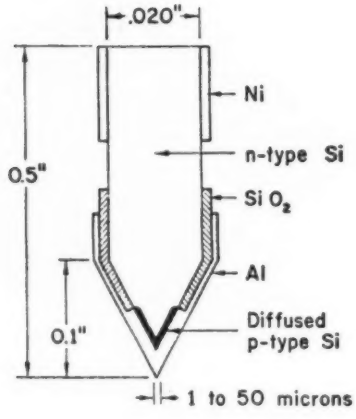

Figure 2. Silicon needle transducer, planar type.

Research with static stress has formed the foundation upon which dynamic exploration can build. Perhaps the most familiar area of static investigation is the direct piezoresistance effect, wherein an applied mechanical force changes the electrical resistance of the material. The piezoresistance effect is characterized by a significant change in the mobility of the majority carriers in the semiconductor (1). In a related investigation, it has been observed that large anisotropic stress causes significant reversible changes in the electrical properties of p-n junctions formed in silicon and germanium. This phenomenon was demonstrated by a radical increase in minority carrier density, as opposed to the majority carrier mechanism of the piezoresistance effect. Since this effect was observed only with the aid of the semiconductor junction, it has been named the piezojunction effect. Dr. J. J. Wortman of the Research Triangle Institute in North Carolina, under sponsorship of the Air Force Office of Scientific

Research, was a principal contributor to the formation of the presently accepted energy-band structure piezojunction model (2).

This model relates the applied mechanical force to an increase in junction current due to a reversible alteration in the material energy gap. Fundamentally, the application of a mechanical stress physically alters the lattice structure (symmetry) of the specimen. The physical aberration is described by means of the semiconductor deformation potential theory. The net result of the applied mechanical force is a shifting of the valence and conduction bands, absolutely and relative to each other. In addition, the degenerate energy levels split and the Fermi level changes relative to the energy-band changes. The underlying feature of these changes is a significant increase in minority carrier density, while such parameters as majority carrier density and mobility remain unaffected as compared to the minority carrier effects. The model, therefore, accounts for the difference between the piezoresistance and piezojunction effects.

The energy-band model does not explain all the observed effects caused by static stress. Generation-recombination centers provide another important stress-induced mechanism. A proposed explanation of the original observations of the piezojunction effect was based on generation-recombination centers. Employing dynamic-stress techniques, it should be possible to define the contribution of the generation-recombination centers to the over-all piezojunction effect.

Initial investigations of the piezojunction effect were static in nature. An "indentor-point" technique was employed, analogous to the phonograph-needle mechanism, to induce large stress levels and to localize the introduction of the mechanical force to the immediate area of the junction. The rigid surface of the indentor point was microscopically aligned so that the mechanical force was applied directly to the semiconductor junction. Since the dimensions involved were so minute, the geometry of the indentor point precluded accurate and reproducible results. To alleviate this problem, the semiconductor "probe" was conceived (Figs. 2 and 3). The p-n junction to be stressed is constructed and shaped at the apex of a needle-like silicon rod. The probe is easily calibrated so that the stress can be induced by pressing the probe against a hard conductive surface. The creation of the probe is a conceptual inversion of the indentor-point technique, in that the reverse procedure is used to apply the mechanical stress (3). Since the probe is essentially a transducer of force and displacement, it was readily translated into the practical world of accelerometers (4). The probe was attached to a housing, and a spring-supported seismic mass was pressed against the semiconductor tip. The mass provided a d-c bias for the instrument and was the motion-sensitive element as well. In addition to being very sensitive to motion, the device is extremely directional. Off-axis response is very limited due to the magnitude of the force required to induce the piezojunction effect (10^4 atmospheres or 1.5×10^5 pounds per square inch). Static testing provided other phenomena-oriented facts for junctions under stress, such as increased fracture level and decreased temperature dependence.

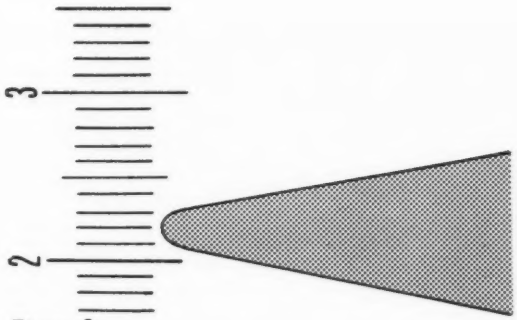

Figure 3.
1 ohm-cm n-type silicon needle. Etching time 3 min. (Each division is 0.04 mm.)

Piezojunction investigation had to be extended into the arena of dynamic forces to fully exploit this useful phenomenon. Under contract to AFOSR, Dr. Wortman has constructed a stress wave "generator" capable of inducing large dynamic stress forces in semiconductor diodes (Fig. 4). This device couples a magnetic drive to a cantilevered bar-shaped sample. The bar specimen is

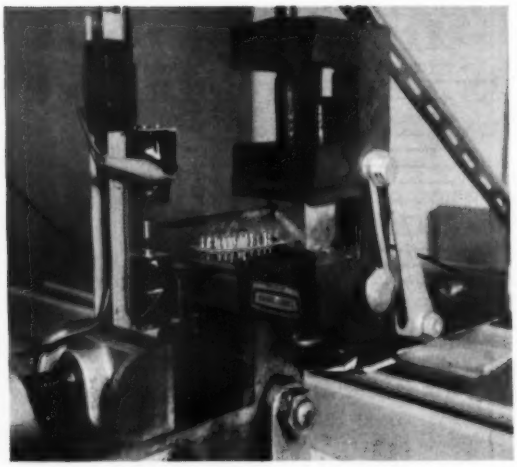

Figure 4. Stress wave generator.

made of n-type silicon approximately 4" × 1/4" × 1/4". Diodes are constructed along the top of the bar, near the center, by adding p-type silicon. Cantilever support is attained by inserting one end of the bar sample into a vise-held nonconductive block, and securing it there with beeswax. A nickel-alloy plate is epoxied to the underside of the unsupported (drive) end of the sample. Electromagnets are positioned above and below the plate, and they are excited by a variable a-c power source. The electromagnets, magnetically interacting with the nickel-alloy plate, cause the silicon bar to oscillate in a vertical plane. Almost no horizontal motion is realized by virtue of the geometry of the mechanism. Thus, the bar is subjected to pure bending stress, and the problem is one-dimensional. Reduction to a single plane of action simplified the mathematical description.

Dr. Wortman has formulated an analytical expression that defines the magnitude of the stress induced in the junction relative to the bar displacement. To measure the oscillatory extremums, a strobelight and elliptical focusing mirror are employed. The displacement directly correlates the incident stimulus and the induced stress forces. Electrical information on junction performance is obtained through gold leads affixed to the junction. Thus the "generator" easily relates the electrical performance of the junction to the induced stress wave. Dr. Wortman's stress wave generator now becomes the basic tool for extending the exploration of the piezojunction effect.

AFOSR research is presently on the threshold of elucidating the dynamic "junction/stress" phenomenon. The potential for applications, as already stated, is outstanding. The horizon of learning appears to be limitless. In effect we, like Dr. Wortman, shall learn by stressing that horizon beyond the fracture point.

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SPECTROSCOPIC STUDIES IN A HIGH-TEMPERATURE HYDROGEN-ARC PLASMA

JOHN C. CORBIN, JR.
Plasma Physics Research Laboratory, ARL

Arc plasmas provide a means of simulating conditions occurring in re-entry plasma sheaths, arc jet thrusters, magnetohydrodynamic generators, and the solar plasma. In the Plasma Physics Research Laboratory of ARL, a vortex-stabilized d-c arc facility has been built and is being used to simulate various plasma conditions. A hydrogen arc at atmospheric pressure and core temperature of about 20,000°C currently provides the plasma source being studied to determine the nature of interaction processes

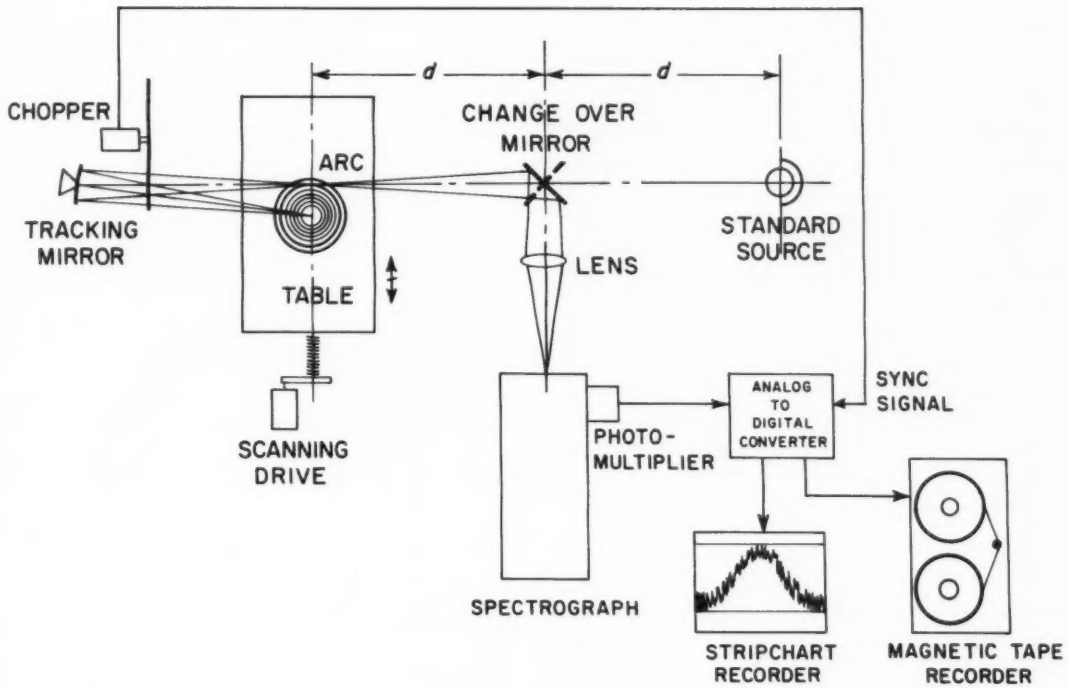

Figure 1. Vortex arc facility.

involved. Spectroscopic measurement of the absorption and emission profile of the plasma is the principal diagnostic technique employed in determining the plasma properties.

Visible radiation from the hydrogen plasma occurs at nominal wavelengths of 6,563Å and 4,861Å, which correspond to the Balmer lines H_α and H_β, respectively. The spectral lines are broadened due to a number of effects, one of which is the Stark effect caused by electric microfields. The half-widths of Stark-broadened hydrogen lines are often used to determine electron densities in the plasma, since such density measurements are not critically affected by local variations in the plasma temperature or departures from thermodynamic equilibrium. In particular, the Balmer line H_β is used where possible because of close agreement between theory and experiment. It has been difficult to check the accuracy of the theory experimentally in predicting the half-width of the Balmer line H_α because this line is strongly self-absorbed at the line center in laboratory plasmas where accurate profile measurements can be made. During the past year this difficulty has been overcome and simultaneous profiles of H_α and H_β have been obtained by the High Density Plasma Dynamics Group under the guidance of Dr. W. G. Braun. Experimental results show that the observed H_α half-widths become larger by about 15% than those predicted theoretically from the H_β half-width. A need for significant modification of the theory of this phenomenon is thus indicated.

A schematic diagram of the vortex arc facility is shown in Figure 1. The arc source is mounted on a table which has a precision scanning drive. A tracking mirror is pivoted and tracks the moving arc so as to always reflect the radiation from the brightest portion of the arc (which serves as the probing radiation) back into the spectrograph. A chopper is inserted in the mirror path and provides for alternate observation of the emitted radiation alone and the superimposed direct and reflected radiation. Current from the photomultiplier in the spectrograph is transformed into a proportional pulse rate.

Thus, digital readings of the intensities are formed and recorded subsequently on magnetic tape during the scanning of the arc column. Spectral emission and absorption coefficients are then obtained using a sophisticated integral transformation of intensity values. These coefficients give the line profiles which are used to determine electron densities. If the relative populations of the first two excited states of hydrogen are assumed to be in local thermodynamic equilibrium with the electrons, the radial profiles of the volume emission coefficient and absorption coefficient at any wavelength in H_α may be used to obtain the radial electron temperature profile of the arc since their ratio must just equal the Planck function evaluated at that wavelength and at the local temperature.

This detailed study of hydrogen, the simplest of all atoms, is only the first phase of a broad investigation of the radiation characteristics of many gases. Instrumentation, computer programs, and operating techniques have been perfected, and the strengths and weaknesses of available theories have been identified. The next step is to include small admixtures of other gases in the now well-known hydrogen environment. Ultimately, complete radiometric data will be obtained for many elements under a variety of conditions of temperature, pressure, and concentration.

Mr. John C. Corbin, Jr. is Deputy Director of the Plasma Physics Research Laboratory, ARL. He has a Bachelor of Electrical Engineering degree from Cornell University (1950), and an M.S. degree in Electrical Engineering from the Ohio State University (1963). He attended the 1964 Summer Institute in Plasma Physics at Princeton University and has taken predoctoral training at Ohio State. Mr. Corbin joined ARL in December 1959 and served successively in the Research Operations Office and the Plans and Analysis Office before joining the Plasma Physics Research Laboratory. He is a Registered Professional Engineer in Ohio, and represents ARL as a Director of the Dayton Chapter, Group on Engineering Management, Institute of Electrical and Electronic Engineers. He is a member of the American Physical Society and two national engineering honor societies, Tau Beta Pi and Eta Kappa Nu.

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three-dimensional

WEATHER-SATELLITE PHOTOS

METEOROLOGY LABORATORY, AFCRL

A method for obtaining a three-dimensional view of clouds photographed two-dimensionally by weather satellites has been reported by John H. Conover of AFCRL and Ronald J. Ondrejka of the Itek Corporation. This method has been used previously for reconnaissance photo interpretation and is simple and straightforward. When two monocular photographs of the same scene are taken with a slight displacement, they provide a stereoscopic pair for three-dimensional viewing with conventional stereo viewers.

The photographs used in the study were transmitted from Nimbus II and recorded with APT (Automatic Picture Transmission) equipment. Nimbus-II photographs were used because the satellite's APT system provides the essential overlap (26 percent) from one photograph to the next. Nimbus II also happens to be at an orbital altitude good for obtaining stereo separation--not the optimum altitude, but good nevertheless.

Good three-dimensional-picture reconstruction from monocular photos does not depend on satellite altitude alone, however. The ratio of the stereo base to satellite altitude is also important. The stereo base is the distance the satellite has traveled between photograph exposures. The time interval between exposures of Nimbus II is 208 seconds, during which time the satellite travels 1,500 km. The altitude of the Nimbus II is 1,180 km. Thus the base-to-height ratio is 1.27. Ratios up to 1.50 are acceptable, although the optimum ratio should be between 0.3 and 1.0.

Obtaining stereo pairs from monocular photographs requires also that the images be on the same scale and that they be of equal image quality and tonal contrast. With respect to this last requirement, AFCRL has made a number of modifications to its APT equipment which have produced satellite photographs with greatly enhanced tonal contrast and definition.

Mr. John H. Conover, a research meteorologist with the Meteorology Laboratory, AFCRL, is presently working in the field of satellite meteorology. His current studies are concerned with the reflective properties of clouds in the visible portion of the spectrum as part of the over-all interpretation of cloud photography obtained from satellites. Mr. Conover attended Swarthmore College from 1934 to 1936. Before coming to AFCRL in 1959, he worked at Harvard's Blue Hill Meteorological Observatory. One of his interests there was the relationship of high clouds to the jet stream. He is listed in American Men of Science, and is a member of the American Meteorological Society. He has written numerous publications. In his early career, these dealt with meteorological instrumentation. Since then, they have been almost entirely on clouds and their interpretation.

With a three-dimensional satellite-photograph presentation, absolute cloud heights can be measured to within a theoretical accuracy of about one km. Actual accuracies to within about two km should be expected

from the Nimbus-II photographs. The true shapes of cloud formations and the angles of cloud slopes are seen in the three-dimensional photos with remarkable clarity. Height resolution is lost, however, because of cloud motion during the exposure interval. This is not altogether a disadvantage because the stereo technique permits the analyst to measure cloud direction and speed (assuming a stable ground reference point is visible on the photographs) with a precision not previously possible from satellite photographs.

upper atmosphere redefined

NORMAN SISSENWINE

Aerospace Instrumentation Laboratory
AFCRL

The U.S. Government Printing Office has recently published a new basic reference document giving atmospheric densities and temperatures up to an altitude of 1,000 km. This new book, bearing the uncompromisingly factual title, U.S. Standard Atmosphere Supplements, 1966, extracts the essence of tens of thousands of observations made by atmospheric physicists all over the world using balloons, rockets, satellites and ground observation equipment. AFCRL, through its extensive measurement program, was the largest single contributor of data to the volume.

Data on atmospheric parameters are essential to the designers of missiles, rockets and supersonic aircraft, and for certain space operations, particularly those associated with re-entry. The reference document was prepared under the auspices of the Committee on the Extension of the Standard Atmosphere (COESA). Thirty organizations, representing the Government, industry, research institutions, and universities, participated in the project. The sponsors of the effort were the Environmental Science Services Administration, NASA, and the Air Force (through the Air Force Cambridge Research Laboratories). AFCRL assumed primary responsibility for editing and publishing the new volume.

Mr. Norman Sissenwine has been Chief of the Design Climatology Branch and senior scientist in the Aerospace Instrumentation Laboratory, AFCRL, since 1963. He joined AFCRC, AFCRL's predecessor, in 1953, serving in responsible positions from the very beginning. He earned his B.S. in Meteorology (1948) "with distinction" at New York University. Mr. Sissenwine is considered an expert on wind and density profiles as related to the vertical flight of missile systems, and is responsible for many of the techniques currently used to evaluate the performance of these systems. He holds several patents, and has received a number of awards for outstanding service to the Government.

The U.S. Standard Atmosphere Supplements, 1966 extends and refines the data contained in the previous COESA document, U.S. Standard Atmosphere, 1962. The new document shows that previous tables for average density were, in general, much too low for altitudes above 150 km. At the equator, for example, densities above 500 km were shown to be more than 100 percent

greater than the data given in the earlier report.

While the 1962 standard atmosphere gave only the idealized midlatitude mean for atmospheric parameters, the new U.S. Standard Atmosphere Supplements, 1966 presents typical winter and summer conditions for various latitudes. The substance of this publication is found in two major sets of tables: those for the region below 120 km, keyed to seasonal and latitudinal variations; and those for 120 to 1,000 km, keyed to solar activity, geomagnetic activity, and solar angle. These two sets of tables, though separated, have mutual boundary conditions so that users are able to select for any location, season, and solar activity the appropriate continuous profiles of atmospheric properties from the surface up to 1,000 km. Profiles of atmospheric properties for any orbital or re-entry trajectory can thus be estimated. In addition, this publication contains information on diurnal variations in density up to 90 km.

AFCRL took the initiative in the preparation of standard-atmosphere tables in 1958 with the publication of the ARDC Standard Atmosphere. The use of satellites and better instrumentation and techniques for the measurement of atmospheric parameters has greatly refined our knowledge of the upper atmosphere and has made obsolete much of the data published before 1960.

The new book may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402.

nuclear spin-lattice relaxation in semiconducting cadmium sulfide

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Nuclear-magnetic-resonance (NMR) spectroscopy is a useful tool for studying the electronic properties of semiconductors since both the frequency of resonance and the nuclear spin-lattice relaxation (SLR) time are dependent upon these properties. The NMR experiment makes use of the effects of static and oscillatory magnetic fields upon a sample containing nuclei with nonzero magnetic moments (spins). In the absence of the oscillatory field, the nuclear spins reach an equilibrium configuration in their Zeeman energy levels, according to Boltzmann statistics, and form a net magnetization along the static field given by

$$M_0 = \frac{N\gamma_n^2\hbar^2 I(I+1)}{3k\theta} B_0 \qquad (1)$$

where N is the number of spins, I is the spin quantum number, γ_n is the nuclear gyromagnetic ratio, $\hbar$ is Planck's constant divided by 2π, k is Boltzmann's constant, θ is the absolute temperature, and B_0 is the static magnetic-field strength. The spin system can be disturbed from its equilibrium configuration by application of an oscillatory magnetic field, B_1, near the resonant (Larmor) frequency, $\nu_L = \frac{\gamma_n}{2\pi} B_0$, usually in the radiofrequency range (about 100 kHz to 100 MHz). If B_1 is strong enough it may "saturate" the spin system, equalizing the populations of the energy levels and thus making M equal to zero.

Our measurements consist essentially of saturating the spin system by application of a large, resonant rf field for a few seconds, then quickly moving the static field off resonance for a time t, and finally sweeping the static field back through the resonance to measure the net magnetization which has accumulated in time t. This magnetization obeys

$$M(t) = M_0(1 - e^{-t/T_1}) \qquad (2)$$

where M_0 is the infinite-time value given by Eq. 1, and T_1 is the relaxation time. The apparatus used for these measurements is

of standard design and is described in several references. (1) We are primarily concerned here with the spin-lattice relaxation mechanisms, that is, the interactions of the nuclear-spin system which allow it to transfer energy to other dynamical systems (the "lattice") in the crystal, such as lattice vibrations, molecular diffusion, or electronic motions.

The first analysis of nuclear SLR in semiconductors was done by Bloembergen, (2) in 1954. He considered the scalar hyperfine contact interaction between the nuclear spins and the spins of nondegenerate electrons in the conduction band. The time dependence of the perturbation, which allows transfer of energy between the two systems, is due to the translational motions of the electrons, and the resulting nuclear SLR time is given by

$$\frac{1}{T_1} = \frac{32}{9} \gamma_e^2 \gamma_n^2 N_e \ell \eta^2 (2\pi m_1 m_2 m_3 k\theta)^{1/2} \quad (3)$$

where γ_e is the electronic gyromagnetic ratio, N_e is the conduction-electron density, ℓ is the number of equivalent minima in the conduction band, η is the electronic density at the nucleus, and m_1, m_2, and m_3 are the anisotropic effective masses. The so-called

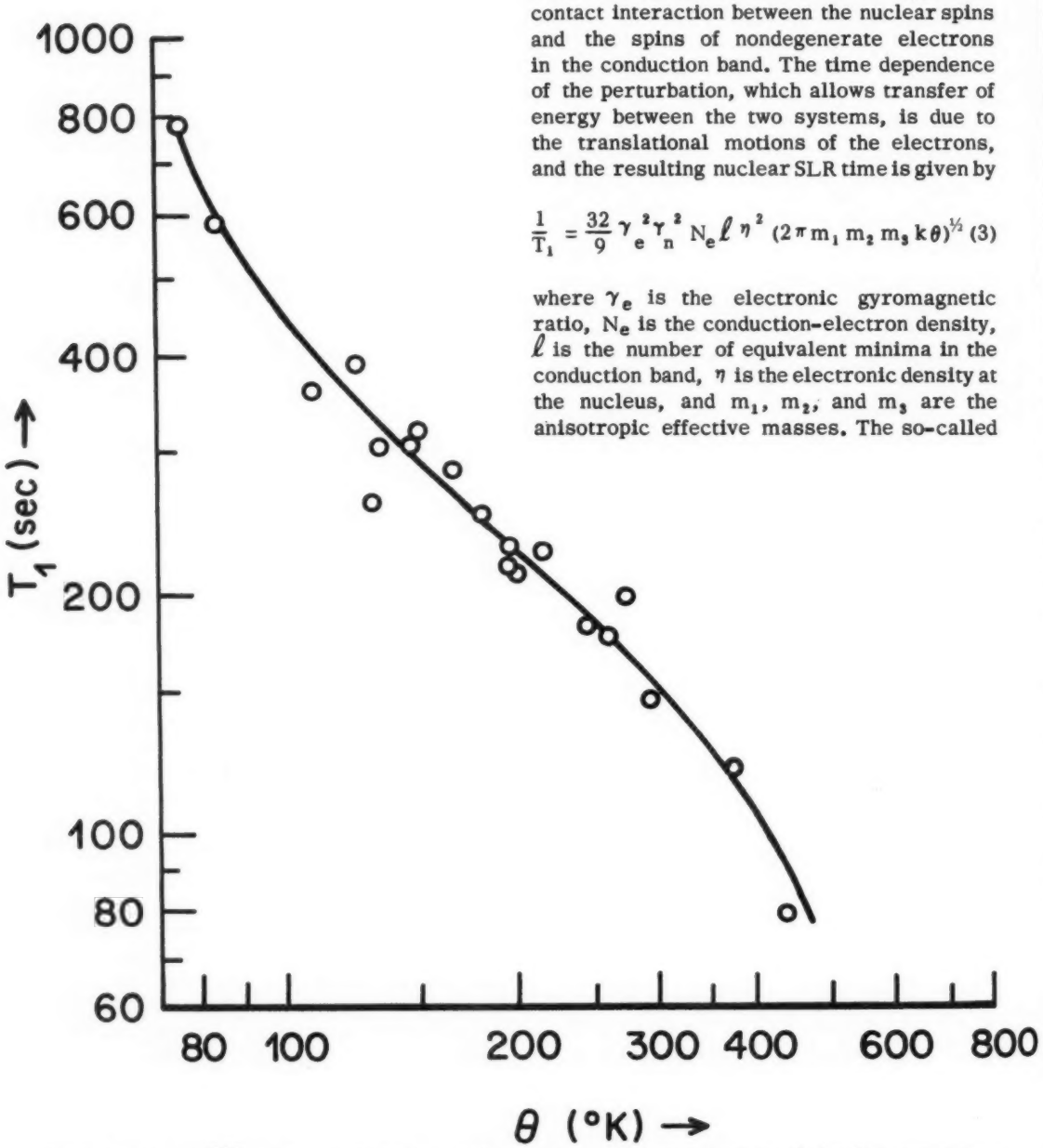

Figure 1. The Cd^{113} nuclear spin-lattice relaxation time (T_1) as a function of absolute temperature (θ) at 7 MHz.

hyperfine constant, A_n, often measured in electron-spin resonance experiments, is related to the parameter η by

$$A_n = \frac{8\pi}{3}\gamma_e\gamma_n\hbar^2\,\eta/v_a \qquad (4)$$

where v_a is an atomic cell volume. The carrier density, N_e, can be determined from Hall mobility measurements, and cyclotron resonance experiments give the effective masses.

We have studied the Cd^{113} spin resonance in a CdS single crystal grown by the vapor-phase-deposition method and having a resistivity $\rho = 3.8\ \Omega$ -cm and a carrier concentration $N_e = 4.4 \times 10^{15}\,cm^{-3}$ at room temperature. The T_1 vs. temperature (θ) data is shown in Fig. 1, and the T_1 vs. resonant frequency (ν) data in Fig. 2. The frequency dependence is noticeable below about 125°K and, at 77°K, $T_1 \propto \nu^{0.4}$. In this low-temperature region, the nuclear SLR can be shown to be almost certainly due to

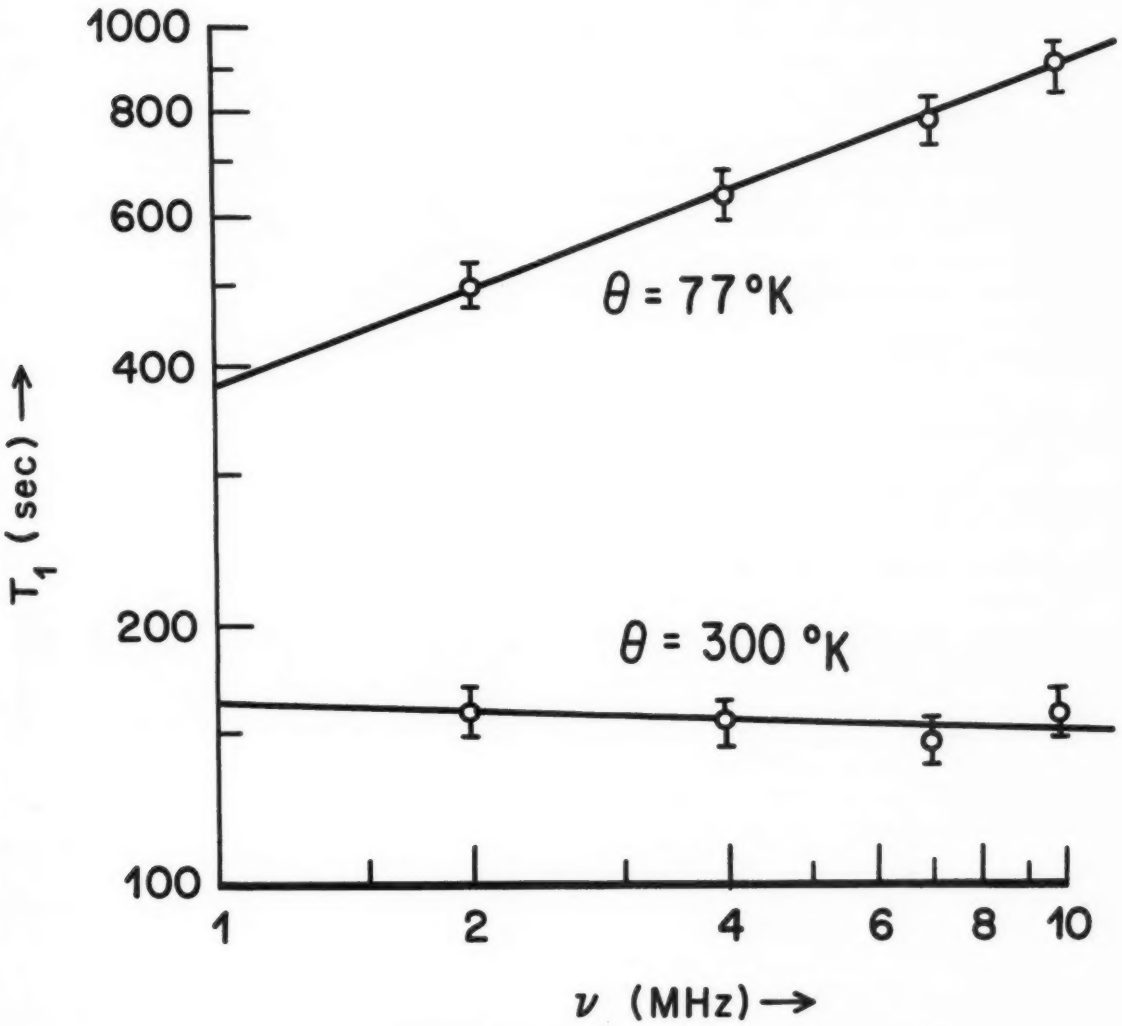

Figure 2. T_1 as a function of resonance frequency (ν) at 77° K and 300° K.

the spin flips of bound, unpaired electrons since analysis of such an interaction predicts $T_1 \propto \nu^{0.5}$, in agreement with experiment, and gives the correct order of magnitude for T_1. The origin of these paramagnetic impurities has not yet been determined.

The first guess for the higher-temperature SLR mechanism would be the conduction-electron interaction since, according to Eq. 3, the T_1 should vary inversely with temperature and be independent of frequency; indeed, Figures 1 and 2 show that both these conditions are true at 300°K. However, two facts invalidate such an explanation: (1) the temperature coefficient of T_1, though of the right sign, has the wrong magnitude, even allowing for the temperature dependence of N_e which was determined from Hall measurements; (2) the absolute magnitude of T_1, using known values of N_e, ℓ, m_1, m_2, m_3, and θ, and an upper limit for the A_n of Eq. 4, is calculated to be about 10^7 sec., much higher than the experimental values.

The reason that conduction electrons are not very effective for nuclear SLR is that they move too fast and the Fourier spectrum of their "collisions" with nuclei has most of its power at frequencies much higher than the nuclear Larmor frequency. As discussed before it is only perturbations with appreciable power near the Larmor frequency that are effective in producing nuclear-spin transitions. An examination of Eq. 3 reveals that electrons of higher effective mass (lower mobility) should therefore give a shorter T_1. Indeed, such low-mobility electrons have often been observed in phenomena of so-called "impurity conduction," which consists of electrons "hopping" between impurity sites. Impurity conduction is usually masked by other conduction processes at temperatures much above that of liquid helium (4.2°K); it was thus not observed in our Hall-conductivity measurements. However, the hopping electrons would be more effective for nuclear SLR because of the longer localization times ("collision" times) at a particular nuclear site.

A reasonable explanation of the data in Fig. 1 would then be as follows: at temperatures below 125°K, the nuclear SLR is mainly due to bound electrons; at temperatures above 200°K, hopping electrons are dominant; the region 125°K to 200°K is a transition area in which both mechanisms are important. It is possible that both the bound and the hopping electrons are part of the same impurity level. If so, at low temperatures most of the electrons would be bound since most of the sites would be filled by electrons from a shallow donor level (known to exist) and there would be few empty sites for the electrons to hop between. At higher temperatures, some of the electrons would be excited out of the

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level, giving fewer bound electrons and more empty sites, thus increasing the hopping rate of the remaining electrons.

The above model is perhaps too simple and more work needs to be done, both experimental and theoretical. However, it seems established that NMR is a useful tool for the study of II-VI semiconductors and will perhaps elucidate some of the areas not open to other experimental techniques.

REFERENCES

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experiments on gas-ionizing transverse shock waves

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The advent of space travel has recently led to an expanded interest in astrophysics and plasma physics. Laboratory astrophysical research generally involves experimenting with a plasma, and considerable effort has gone into attempting to produce uniform plasmas where all flow parameters are known. One such attempt is in progress at the University of Colorado in an inverse pinch shock tube (1) under the direction of Dr. George Vlases. In a co-operative effort with Dr. Vlases, Capt Charles Stebbins of the Aerospace Mechanics Division, FJSRL, and Cadets Duane Clawson and Jeff Hurt of the United States Air Force Academy have investigated ionizing shock waves both experimentally and theoretically.

The particular problem being studied involves propagating a very fast shock wave (Mach numbers of 50 to 100) into a cold gas which has imbedded in it a magnetic field whose flux lines are perpendicular to the velocity vector of the shock wave. This particular type of shock is called a transverse ionizing magnetohydrodynamic (MHD) shock wave. It is unusual in that: 1) the plasma, or hot gas behind the wave, can interact with the transverse magnetic field; and 2) the jump conditions across the gas-ionizing shock wave cannot be solved for in closed form as the conservation equations, in conjunction with Maxwell's equations, involve 3 equations in 4 unknowns: the plasma density, ρ, the electric field in the plasma, E, the plasma magnetic field, B, and the plasma enthalpy, h. It has been proposed that E, for instance, is arbitrary, or that ρ is uniquely determined by a condition similar to that in detonation-wave analysis. However, Lyubimov and Kulikovskii (2) and, later, Chu (3) have proposed that the missing relation is supplied by the structure of the shock wave itself. In particular, these authors indicate that the shock tends to an ordinary shock for low plasma temperatures, and to an MHD shock (shock propagating into a hot gas) for high plasma temperatures, both cases being uniquely describable by conservation equations alone.

Measurements of E, B, and shock velocity, u_s, were made in the inverse pinch device in low-pressure hydrogen, and were integrated with a computerized state equation for equilibrium real-gas effects to provide a theoretical/experimental comparison for the plasma parameters. The state equation (4) was programmed into the digital computer at the USAF Academy by Cadets Duane Clawson and Jeff Hurt. The experimental measurements indicated that the magnetic-field compression across the shock was zero for the low plasma temperatures (ordinary shock), and that it tended to the same value as the density jump across the shock for high plasma temperatures (MHD shock). The preliminary experimental results, then, indicate that the Lyubimov-Kulikovskii-Chu analysis is correct and, further, Ohm's law for the uniform plasma, $\vec{E} = -\vec{u} \times \vec{B}$, is verified. Thus, the inverse pinch/ionizing shock method of plasma production has been verified to afford one a stable, reproducible and fully understood plasma for laboratory astrophysical applications.

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Shown in front of the tape units of the FJSRL digital computer are Cadet Duane Clawson and Captain Charles F. Stebbins. Cadet Clawson, of Pittsburgh, California, is majoring in Aeronautical Engineering at the United States Air Force Academy. He has spent the past year as a research assistant with Captain Stebbins on the independent research project described here.

Captain Stebbins is a 1961 graduate of the USAF Academy. He has an Aeronautical Engineering degree from the California Institute of Technology and a Ph.D. in Aerospace Engineering Sciences from the University of Colorado. He has been a research associate in the Frank J. Seiler Research Laboratory since 1963 and currently holds the academic rank of Assistant Professor of Aeronautics at the USAF Academy.